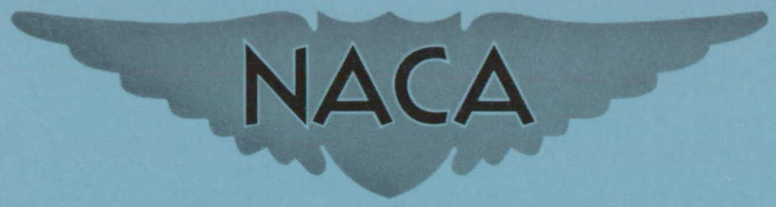
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RESEARCH MEMORANDUM

PRELIMINARY DATA ON RAIN DEFLECTION FROM AIRCRAFT WINDSHIELDS BY MEANS OF HIGH-VELOCITY JET-AIR BLAST

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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3736

SUMMARY

A preliminary experimental investigation is being conducted to determine the feasibility of preventing rain from impinging on aircraft windshields by means of high-velocity jet-air blast.

The results indicate that rain deflection by jet blast appears feasible for flight speeds comparable with landing and take-off speeds of interceptor-type jet aircraft; however, attainment of good visibility through the mist generated by raindrop breakup presents a problem. For the simulated windshield and the lower windshield angles used in the investigation, air-flow rates of the order of 3.3 pounds per minute of unheated air per inch of windshield span were required for adequate rain deflection at a free-stream velocity of 135 miles per hour.

A method has been devised whereby it is possible to produce large-diameter water drops (1000 to 1500 μ) in a moving air stream, without breakup, at speeds in excess of 175 miles per hour.

INTRODUCTION

Obtaining good removal of water from airplane windshields for better visibility during flight through rain is becoming an increasingly important problem in regard to flight safety. The need for good rain removal is especially acute during airplane descent and landing. The high landing speeds of modern interceptor-type airplanes is probably the major single factor contributing to the need for better rain removal systems. However, in some cases, the design of an airplane and its pilot enclosure is such that during landing, even under good weather conditions, the forward field of vision is limited to such an extent that any further decrease in visibility could be detrimental to flight safety. Pilot reports indicate that, when making runway landings in rain with present operational interceptor-type aircraft having an inadequate or no rain removal system, many pilots make their observations almost entirely through the side panels because of extremely bad forward visibility.

Because of the growing seriousness of the problem, the NACA Lewis laboratory is conducting a preliminary investigation to study the possibilities of preventing rain from impinging on aircraft windshields at flight speeds comparable with landing and take-off speeds of jet aircraft. The system being investigated is one wherein raindrops are broken up by means of a high-velocity air blast and the resulting mist is deflected around the windshield without impingement. Such a system has several inherent advantages. Air jets employed may be mounted flush to the fuselage or easily streamlined and thus would not penalize the airplane aerodynamically for high-speed flight. The high air-handling capacities of present jet engines, together with the high pressures and temperatures available, add to the desirability for using such a system. Thrust losses due to bleeding the compressor for air used to deflect the raindrops are in most cases so small (less than 1/2 percent) as to be negligible, even for take-off. A system of this type employing heated air and capable of providing adequate rain removal (or deflection) could probably serve also as an excellent windshield anti-icing system.

3736

The present study is being conducted in the 2- by 20-inch tunnel at the NACA Lewis laboratory. Because the investigation is still preliminary in scope, the experimental study is restricted almost entirely to the mechanics of water-drop breakup by high-velocity jet-air blast and to the determination of the over-all feasibility of such a system. Thus far, all work has been done with unheated air jets operating in choked flow and discharging from straight circular tubes.

APPARATUS AND PROCEDURE

A schematic drawing of the tunnel test section with simulated windshield, raindrop discharge nozzle, and air-jet discharge tubes installed is shown in figure 1. The water discharge nozzle, which provides a single stream of drops, is located just upstream of the beginning of the test section. Air jets discharge through straight circular tubes positioned at various distances forward of the windshield and directed at various angles to the main air stream.

The simulated windshield, made of Lucite, is 2 inches wide and 12 inches long along the slant face. An afterbody is provided to better simulate a windshield-canopy combination. The windshield angle may be varied from 25° to 90° by means of hinges incorporated in the windshield design and slots provided in the Lucite portion of the test-section wall (see fig. 1). With the exception of the Lucite portion, the test-section walls are optically flat glass installed to enable photographing by means of schlieren apparatus. The schlieren apparatus consists of a single mirror system of conventional design but incorporating a microsecond flash arrangement. Air-jet discharge tubes are positioned to discharge at angles of 30°, 45°, 60°, and 90° to the main air stream

and to intersect the plane of the tunnel floor (removable block) at a surface distance of 3/4 inch ahead of the windshield leading edge. In addition to the 3/4-inch location, jets discharging at the 90° angle may be positioned at a distance of $2\frac{1}{2}$ and 4 inches ahead of the windshield. For that portion of the investigation which included the simulated windshield, the vertical distance from tunnel floor to the open end of the discharge tubes ranged from 1/2 to 3/4 inch.

3736

CS-1 back

Because the raindrop nozzle was designed to operate at high water discharge velocities and pressures, it was necessary to provide a high-pressure supply system capable of handling working pressures of the order of 1000 pounds per square inch maximum. A schematic diagram of the water supply system together with an over-all sketch of the test arrangement is shown in figure 2. The system is tied directly to the domestic water line and is operated in the following manner: With the high-pressure nitrogen supply line closed by means of two hand valves, (8) and (9a), the bleed (10) is opened by means of a hand valve (9c). By opening valve (9b), ordinary tap water is allowed to flow directly from the supply line (12), through the filter (13), and into the supply tank (CO_2 bottle (11)). With the supply tank full, the water supply valve and bleed are closed, the nitrogen supply line (9a) is opened, and the pressure regulated to the desired value by means of the regulating valve (8). Water may then be delivered through the flexible hydraulic line (14) to the water nozzle (2), which consists of the hypodermic needle ($1\frac{3}{4}$ in. long) mounted on the end of a 4-foot straight length of stainless steel tubing having an inside diameter of 1/4 inch. In order to minimize air-flow turbulence around the needle, the abrupt step existing at the junction between the needle and tube (ratio of tubing to needle diameter is approximately 9.5) was filled with solder and faired to provide a smooth fillet. Internally, a transition piece provides a converging nozzle-type flow to the needle entrance. The exit end of the needle is ground square with only the burrs removed. The needle end of the stainless steel tubing was supported between the bellmouth walls by means of a spring-wire arrangement to suppress vibration effects and to obtain better directional control of the raindrop stream.

RESULTS AND DISCUSSION

In flight through rain, essentially all the raindrops directly ahead of the airplane windshield will come on to strike the windshield even at the lower landing speeds. Because these raindrops are large in diameter and mass, and consequently possess great inertia, they cannot follow the air streamlines around the windshield but go on to strike the windshield surface and thus obscure vision. However, if these large raindrops can be broken up into very fine water droplets somewhere ahead

of the windshield, then the resulting fine droplets will follow the air streamlines approximately and flow around the windshield without impingement. One method for achieving raindrop breakup is by means of a series of high-velocity air jets located some nominal distance (in.) ahead of the windshield.

In order to study this raindrop disintegration by jet blast, it was first necessary to produce raindrops at tunnel air velocities of about 150 miles per hour. Unless special precautions are taken, however, water drops of raindrop size break up when subjected to the accelerations necessary to bring their velocity up to tunnel air speed. Therefore, the first phase of the investigation was conducted for the purpose of devising a means for producing water drops of raindrop size in a wind tunnel and at speeds comparable with landing and take-off speeds of jet airplanes.

3736

Method for Producing Raindrops

This initial portion of the investigation was conducted for the purpose of developing a nozzle or technique whereby water drops having acceptable average diameters in the range from 1000 to 1500 microns could be produced (without breakup) at free-stream velocities comparable with landing and take-off speeds for jet aircraft. At present, drops in this diameter range can be produced at air-stream velocities up to about 180 miles per hour. The drops are formed by discharging a solid jet of water from a hypodermic needle (0.021-in. I.D.) at a velocity approximately equal to that of the surrounding air flow. The water discharges from the needle in a solid stream for a distance of about 4 to 6 inches, then quickly breaks up into a narrow band of water drops having a maximum diameter of about 1600 microns. The smaller drops are approximately 1000 microns in diameter. The estimates of drop diameters were obtained by direct measurement from enlargements of photographs and therefore constitute only approximate values. This method for producing large-diameter drops in a fast-moving air stream eliminates much of the problem of drop breakup associated with high rates of acceleration. The method has a principle disadvantage in that the quantity of water approaching the simulated windshield is far in excess of that which would be encountered during flight in normal rainfall. Water pressures necessary to obtain these high discharge velocities range from about 200 pounds per square inch for a free-stream velocity of 100 miles per hour to 800 pounds per square inch for a free-stream velocity of 200 miles per hour.

An example of the size and number of drops produced by this system is presented in figure 3. The photograph shows the narrow band of water drops passing through the tunnel test section for a free-stream velocity of 100 miles per hour. The simulated windshield and air jets were not present in the test section at the time the picture was taken. The drops are essentially spherical in shape, but visual studies with stroboscopic light give evidence that the drops are undergoing distortions due

to aerodynamic forces or surface tension as the drop seeks to establish a true spherical shape. The photograph shown was taken at the upstream end of the test section (about 8 to 12 in. from the hypodermic needle), but the drops travel through the entire length of test section (3 ft) without further change. The photograph was taken by means of a single-mirror schlieren apparatus which provides results having a double image as noted in the figure. The image displacement takes place in a plane almost perpendicular to the line of droplet travel.

3736

Rain Deflection by Jet Blast

The single stream of drops presented in figure 3 provides a means for studying raindrop - air-jet interaction (fig. 4). The photograph shows a stream of drops being torn apart by means of a high-velocity air jet discharging from a straight tube having a 1/8-inch inside diameter. The air jet is discharging at an angle of 45° to the air stream and at an exit total pressure of 39 pounds per square inch (bench tests were conducted to determine pressure losses through the air supply system). The free-stream velocity is 100 miles per hour, and the drops are passing through the test section at a vertical distance of about $1\frac{3}{4}$ inches above the point of air-jet discharge or approximately $2\frac{3}{4}$ inches above the tunnel floor. The photograph shows that rapid and rather complete breakup of drops is achieved by means of the high-velocity air jet. The dark area downstream of the point of air-jet - raindrop interaction represents the dense mist containing the many fine droplets created by raindrop breakup.

Initial tests with the simulated windshield were made with jets discharging almost parallel to the windshield to determine the amount of raindrop breakup and windshield scrubbing action achieved. A photograph showing a single 1/8-inch-diameter air jet impinging at a slight angle on the windshield is presented in figure 5 for a free-stream velocity of 120 miles per hour. The air-jet-exit total pressure is 52 pounds per square inch, the jet discharge angle is 30°, and the windshield angle is 33°. Oncoming drops are broken up just before they contact the windshield surface, but the point of breakup is so close that the resulting spray goes on to strike the windshield. With this arrangement, a great portion of all the water ahead of the windshield comes on to strike the windshield in the form of mist. Because unheated air was used throughout the investigation, the figure shows that mechanical action of the jets alone will not provide rain removal adequate for good visibility for the case where cold-air jets impinge on the windshield. Such a system would have to rely heavily on evaporation of the mist by hot-air jets to provide good visibility. Whether the necessary rapid evaporation can be obtained with hot-air jets is a subject for future study.

Increasing the angle between the air jets and the windshield (fig. 6) results in better and more complete breakup of the raindrops. The mist now has been lifted vertically and moved further away from the windshield so that much of the spray misses the windshield entirely. Conditions for figure 6 are as follows: free-stream velocity, 120 miles per hour; air-jet diameter, 1/8 inch; jet pressure, 52 pounds per square inch; jet discharge angle, 60°; windshield angle, 40°.

The jet discharge angle was further increased with resulting increases in the amount of rain deflection obtained until a maximum of 90° to the main air stream was attained. At this angle a single 1/8-inch-diameter air jet was still insufficient to provide adequate rain deflection for the simulated windshield used and was therefore replaced with a jet discharge tube having an inside diameter of 1/4 inch. A single 1/4-inch-diameter air jet discharging at 90° and operating at an exit total pressure of approximately 35 to 40 pounds per square inch provided adequate rain deflection at the lower windshield angles (30° to 35°). However, deflection was adequate only for the cases where it was possible to maintain the raindrop stream directed on the centerline of the single air jet. Any appreciable deviation of the water drops from the jet centerline resulted in mist striking the windshield surface. Two additional 1/4-inch jet discharge tubes were therefore added, giving a total of three 1/4-inch jets equally spaced across the 2-inch span of the tunnel. The results obtained with this configuration and a 90° discharge angle are presented in figure 7. The free-stream velocity is 100 miles per hour, the windshield angle is 32°, and the jet-exit total pressures are 35.5, 25.2, and 15.5 pounds per square inch for figures 7(a), (b), and (c), respectively. For the conditions presented in figure 7(a), all the mist resulting from raindrop breakup has been deflected to miss the windshield entirely and there is no water present on the windshield surface. At the top of the windshield, the mist misses the windshield by approximately 1 inch. Based on an arbitrary flow coefficient of 0.90, the total jet-air flow is 6.5 pounds per minute or 3.25 pounds of air flow per minute per inch of span of windshield. For conditions presented in figures 7(b) and (c), considerable water is still impinging on the top of the windshield.

Increasing the free-stream velocity from 100 miles per hour (fig. 7(a)) to 150 miles per hour resulted in an expected decrease in the amount of rain deflection obtained as shown in figure 8. Conditions of figure 8 are identical to those of figure 7(a) with the exception of the free-stream velocity. For this case the mist is striking the windshield about 1 to 2 inches from the top. While the stream velocity was being raised from 100 to 150 miles per hour with the total jet-air flow held constant at 6.5 pounds per minute (exit pressure of 35.5 lb/sq in.), the mist began striking the uppermost portion of the windshield at a free-stream velocity of about 135 miles per hour.

3736

The level at which the drops enter the test section has little effect on the amount of water deflected around the windshield for a particular condition. If the drops approach the lower portion of the windshield, they encounter the higher-velocity portion of the air jets and the resulting mist is still contained within essentially the same boundaries. For the three-jet configuration, attempts were made to penetrate the air blast by directing the raindrops into regions near the tunnel floor (between jets) where the jets have not yet expanded sufficiently to provide a solid front. It appeared that the effects of the high-velocity jets would still break up the raindrops and deflect the mist around the windshield; however, difficulties encountered because of the arrangement of the experimental apparatus precluded the obtaining of definite results in this respect. During these attempts to direct the raindrops near the tunnel floor, it was noted that water flowing along the surface would be picked up in the plane of the discharge tubes and entrained in the jet-air blast. The three-1/4-inch-jet configuration operating at an exit total pressure of 35 pounds per square inch picked up surface water even when the jet discharge tubes protruded 1/4 inch above the surrounding surface.

Although rain deflection by high-velocity-air blast appears feasible at landing and take-off speeds for jet aircraft, the mist produced by raindrop breakup still presents a visibility problem. The present method for producing raindrops gives water-flow rates far in excess of what would be encountered in normal rainfall; as a result, the mist shown in the photographs is so dense that it is not possible to see through it. Based on the frontal area of the windshield, the rates of water interception range from about 10 times that which would be encountered during flight in a heavy shower to approximately 30 to 40 times that for the light steady rains. At present, work is being directed toward devising a means whereby it will be possible to provide water-flow rates approaching the windshield comparable with those in flight and at the same time to maintain the minimum drop diameter to at least 1000 microns at all free-stream velocities. (Bench tests conducted on a pump-nozzle combination designed to provide the required flow and drop diameters appear promising.) It may be that, even for normal amounts of water, the mist formed by drop breakup will still present a visibility problem. If this occurs, further studies will be conducted to determine the amount of evaporation of these mist droplets that might be attained by the use of hot air for the rain-deflecting jets.

CONCLUDING REMARKS

The results obtained thus far in a preliminary investigation to determine the feasibility of an aircraft-windshield rain-deflection system using jet-air blasts indicate that

3736

1. Rain deflection by jet blast appears feasible for flight speeds up to at least 150 miles per hour for low-angle windshields (35° or less); however, visibility through the mist generated by raindrop breakup presents a problem.

2. For the simulated windshield used, air-flow rates of the order of 3.3 pounds per minute of unheated air per inch of windshield span were required for adequate rain deflection at a free-stream velocity of 135 miles per hour. The air-flow rate is equivalent to that obtained with three 1/4-inch-diameter jets equally spaced across the 2-inch span of windshield (32° windshield angle) and operating at 35-pound-per-square-inch exit total pressure.

3736

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 18, 1955

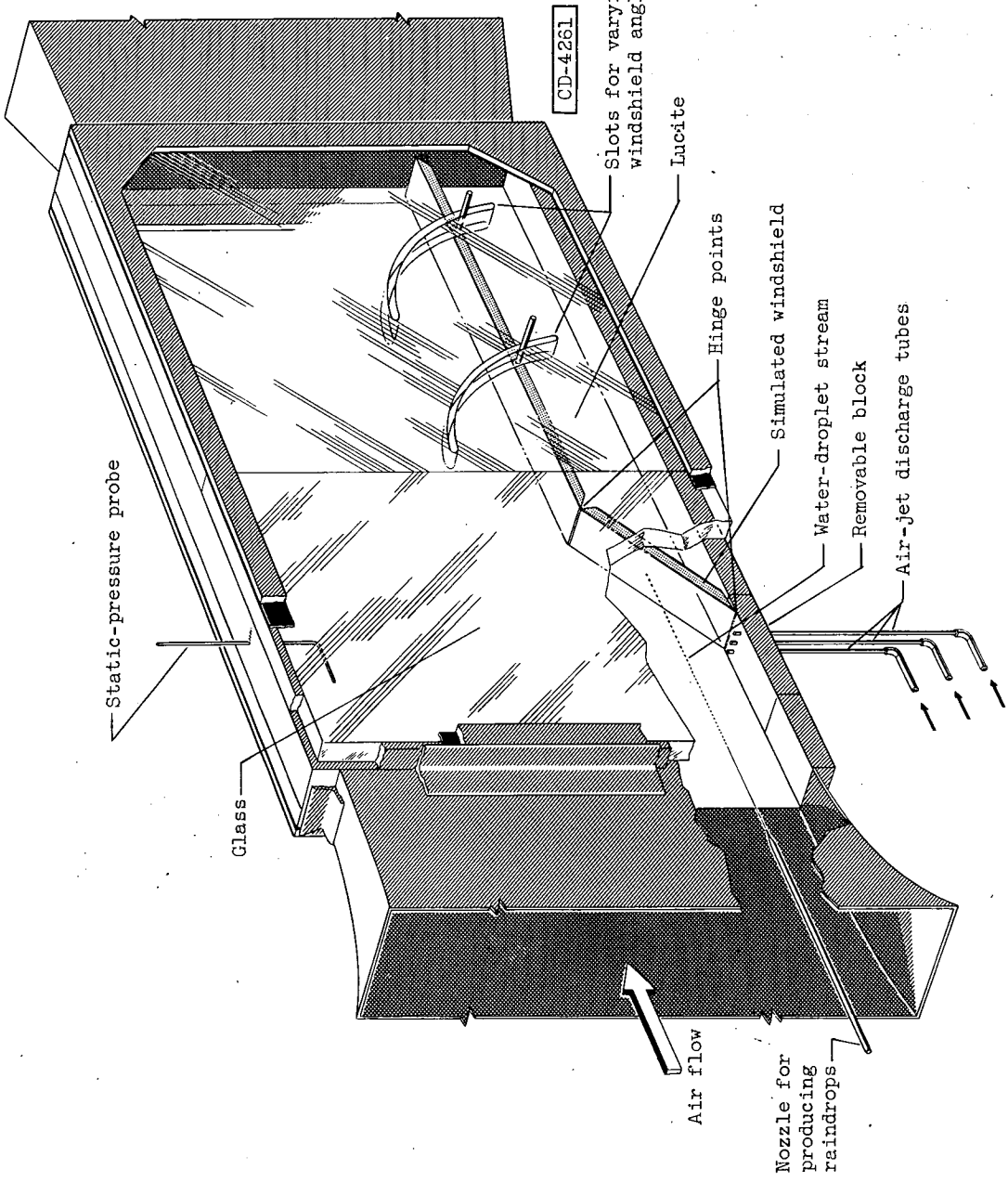
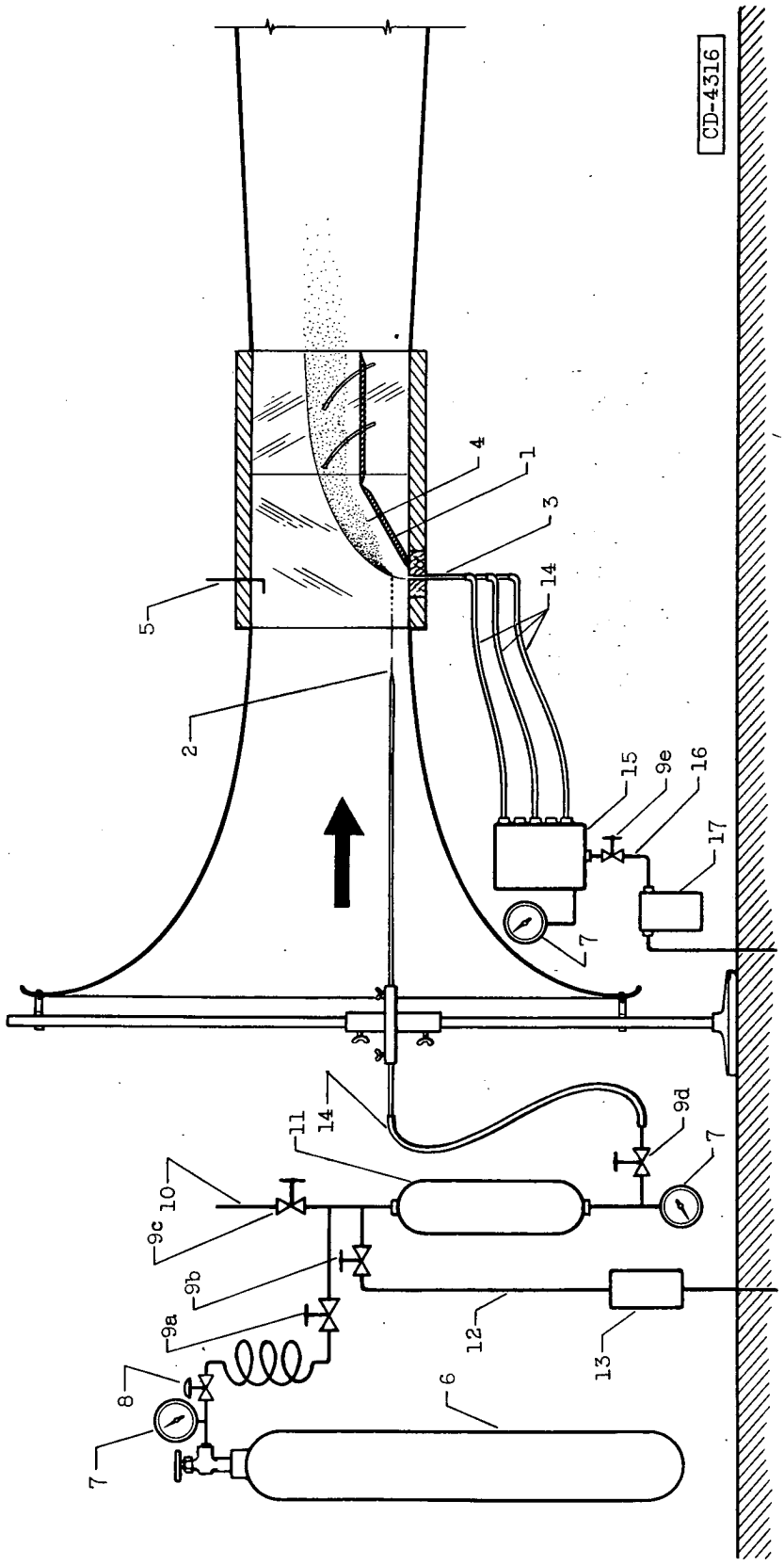


Figure 1. - Schematic diagram showing test section of 2- by 20-inch tunnel with simulated windshield, raindrop nozzle, and air-jet discharge tubes installed.

CS-2 3736



1. Simulated windshield
2. Water discharge nozzle (hypodermic needle)
3. Air-jet discharge tubes
4. Mist formed by rain-droplet breakup
5. Static-pressure probe
6. Nitrogen bottle
7. Pressure gages (3)
8. Pressure regulating valve
9. Hand valves
10. Bleed
11. Water supply tank (CO_2 bottle)
12. Water supply line
13. Water filter
14. Flexible lines
15. Plenum chamber
16. Air line
17. Air filter

Figure 2. - Schematic diagram showing arrangement of apparatus used in windshield rain-deflection studies.

3736

CS-2 back

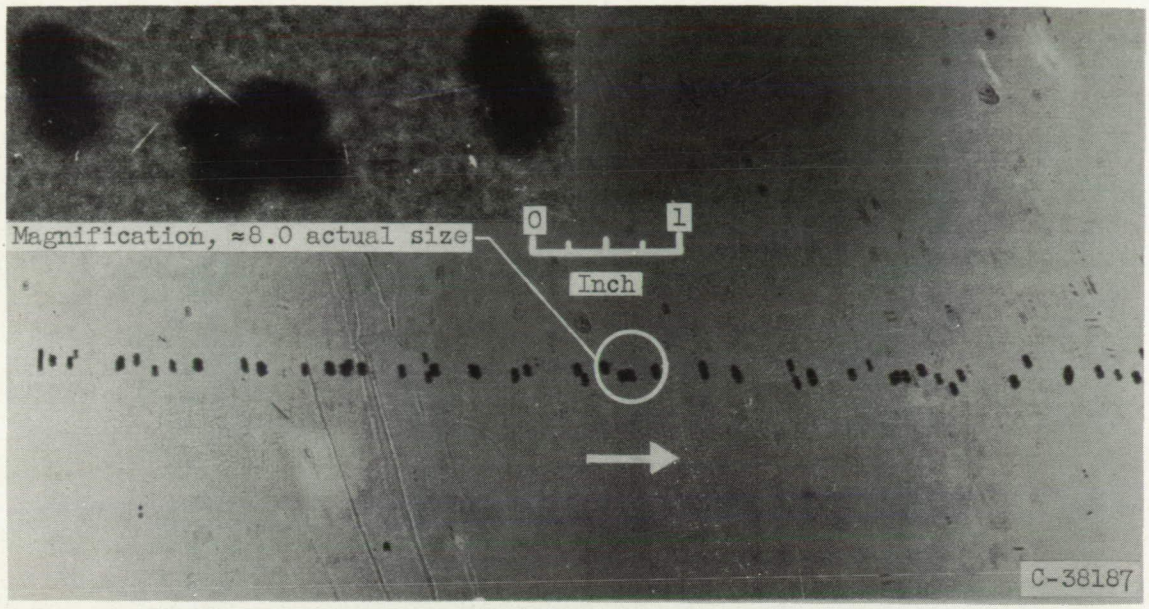


Figure 3. - Schlieren photograph of water-drop stream passing through test section of 2- by 20-inch tunnel for free-stream velocity of 100 miles per hour. (Note double image.)

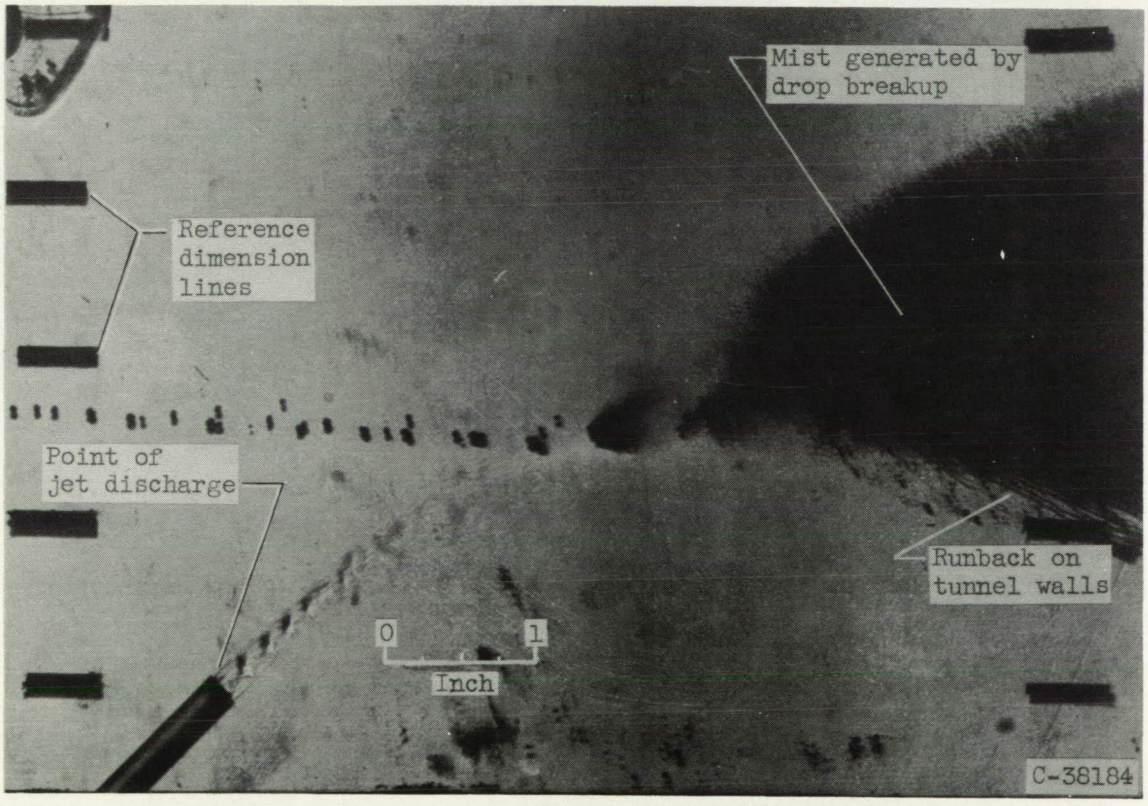


Figure 4. - Breakup of water drops by means of single high-velocity air jet. Air-jet diameter, 1/8 inch; air-jet total pressure, 39 pounds per square inch; jet discharge angle, 45°; free-stream velocity, 100 miles per hour.

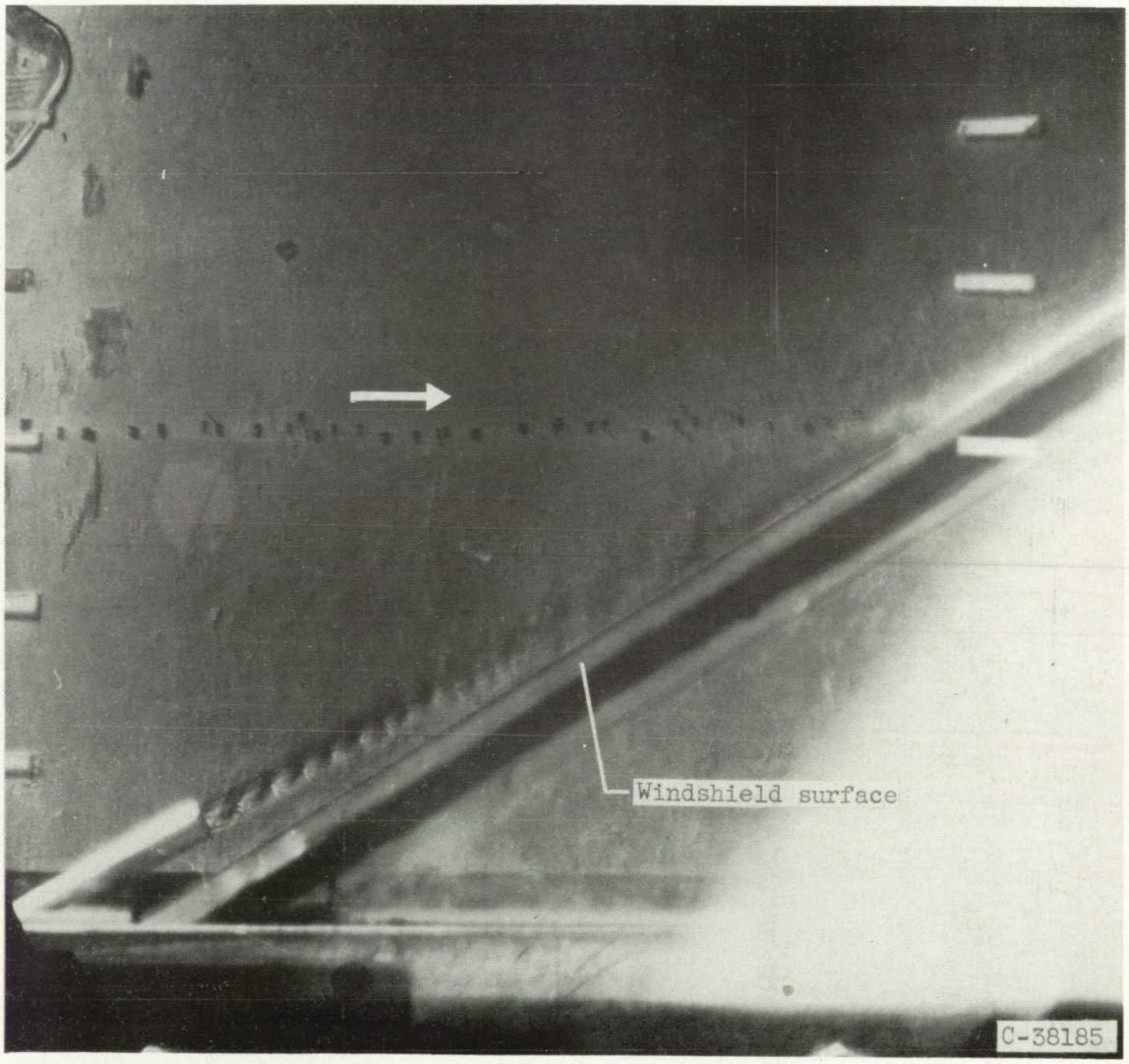
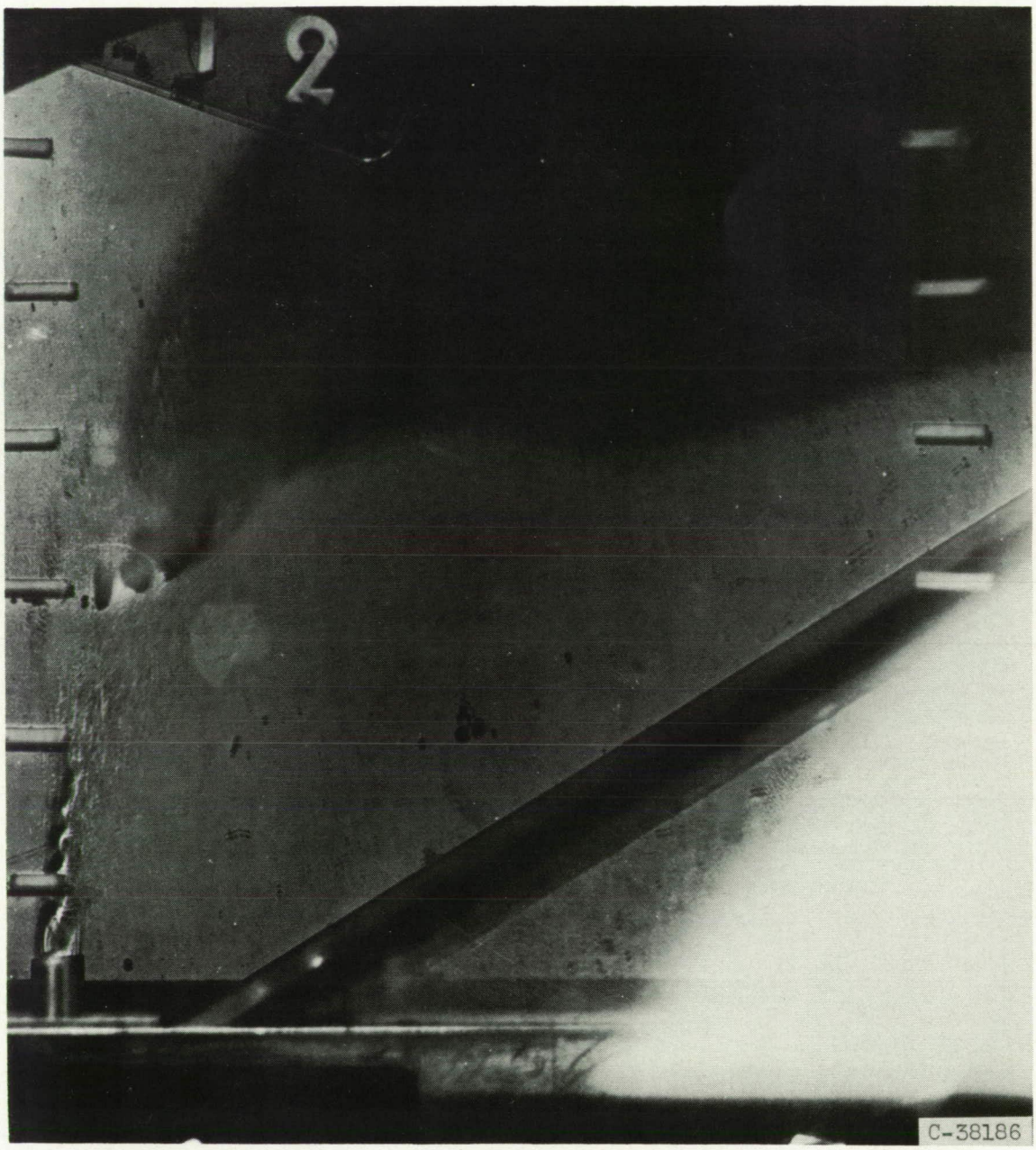


Figure 5. - Water-droplet breakup by means of single high-velocity air jet impinging at slight angle to windshield surface. Air-jet diameter, 1/8 inch; air-jet-exit total pressure, 52 pounds per square inch; air-jet discharge angle, 30°; windshield angle, 33°; free-stream velocity, 120 miles per hour.

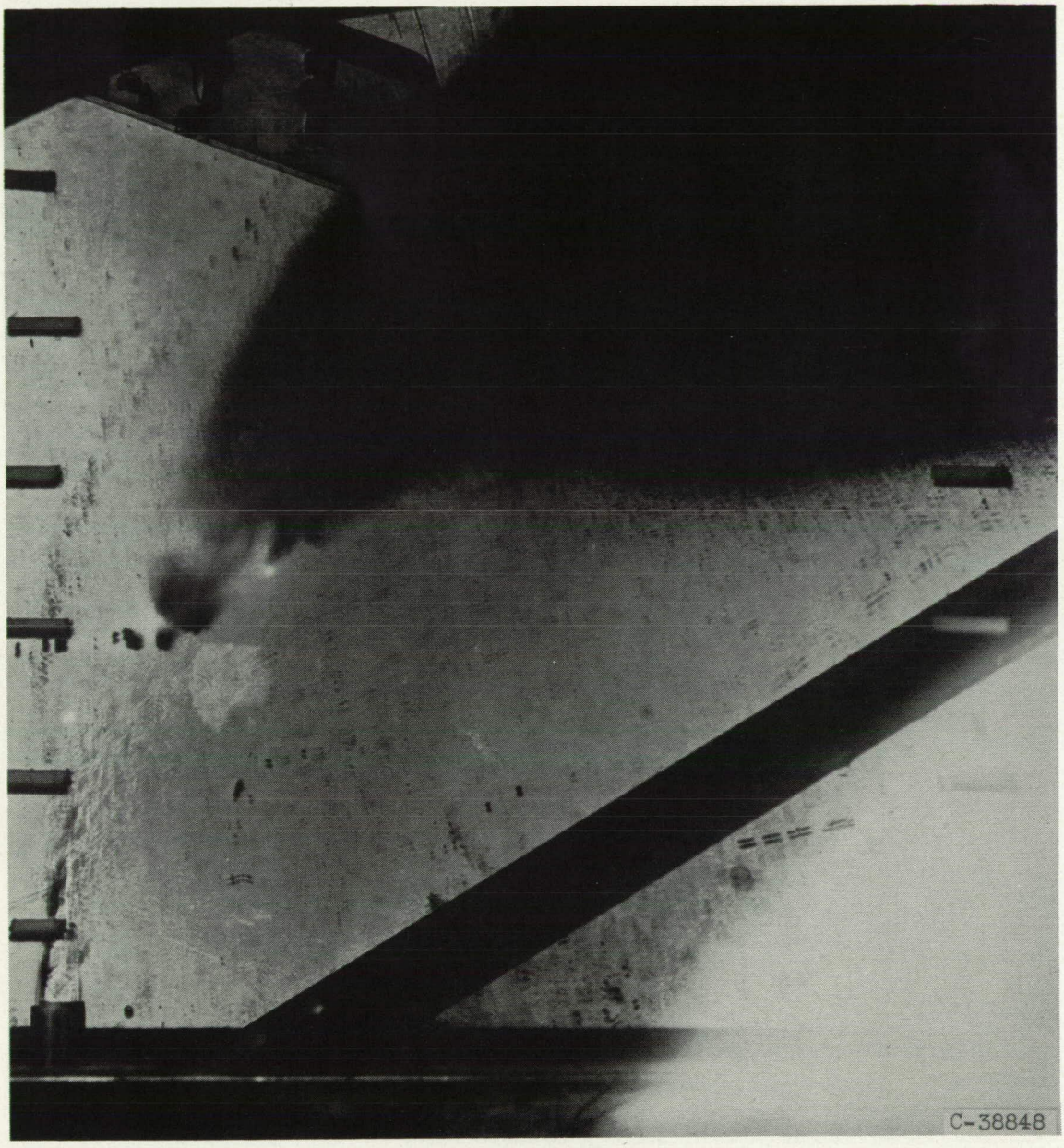


Figure 6. - Raindrop breakup and deflection achieved with single air jet operating at 10° included angle between jet and windshield. Air-jet diameter, 1/8 inch; air-jet total pressure, 52 pounds per square inch; jet discharge angle, 60°; windshield angle, 40°; free-stream velocity, 120 miles per hour.



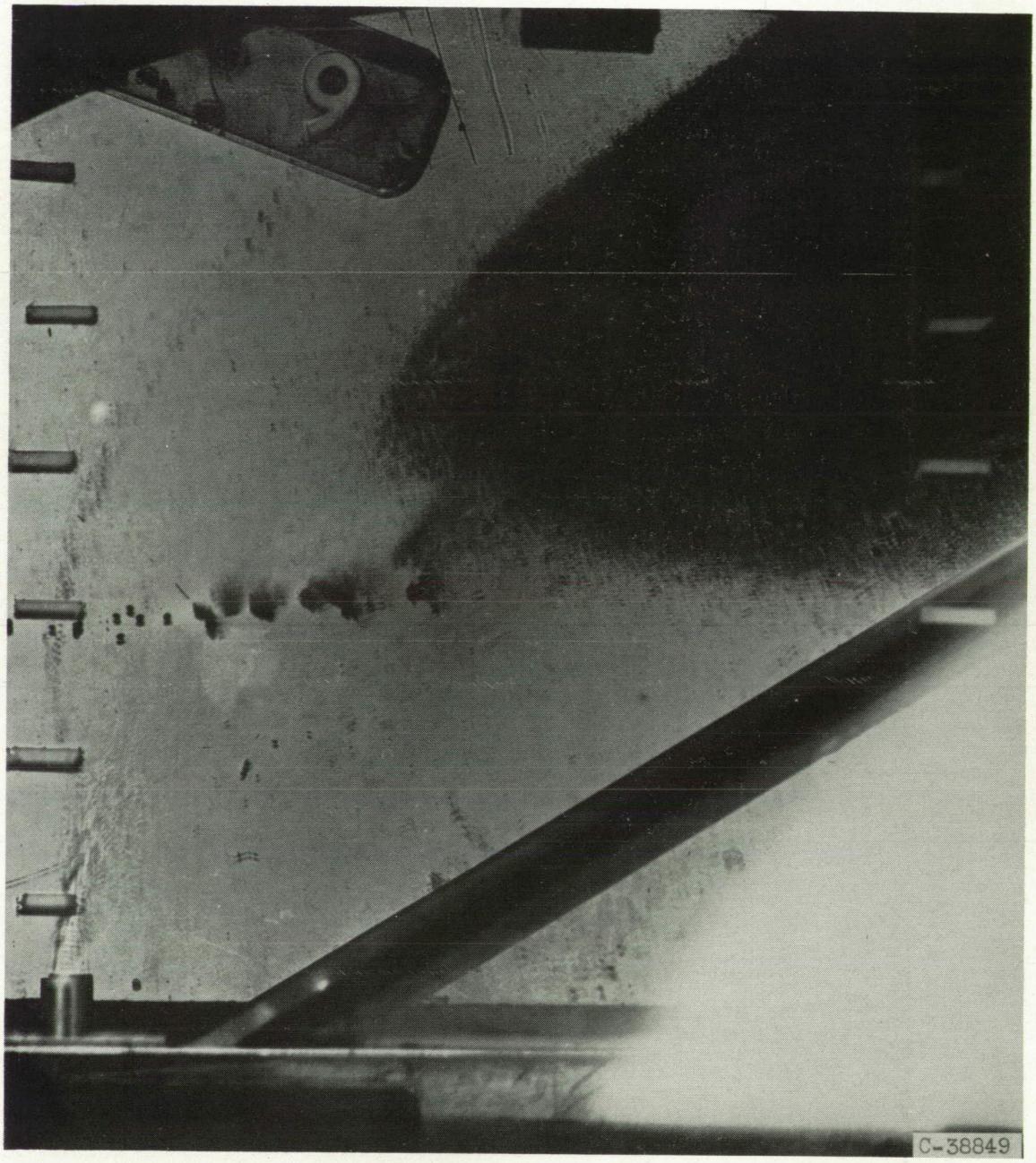
(a) Air-jet-exit total pressure, 35.5 pounds per square inch; total jet-air flow, 6.5 pounds per minute.

Figure 7. - Variation of rain-deflection effectiveness with air-jet pressure. Three 1/4-inch-diameter air jets, equally spaced; jet discharge angle, 90°; windshield angle, 32°; free-stream velocity, 100 miles per hour.



(b) Air-jet-exit total pressure, 25.2 pounds per square inch; total jet-air flow, 4.2 pounds per minute.

Figure 7. - Continued. Variation of rain-deflection effectiveness with air-jet pressure. Three 1/4-inch-diameter air jets, equally spaced; jet discharge angle, 90°; windshield angle, 32°; free-stream velocity, 100 miles per hour.



(c) Air-jet-exit total pressure, 15.5 pounds per square inch; total jet-air flow, 3.2 pounds per minute.

Figure 7. - Concluded. Variation of rain-deflection effectiveness with air-jet pressure. Three 1/4-inch-diameter air jets, equally spaced; jet discharge angle, 90°; windshield angle, 32°; free-stream velocity, 100 miles per hour.



Figure 8. - Rain-deflection effectiveness at free-stream velocity of 150 miles per hour. Three 1/4-inch-diameter air jets, equally spaced; jet discharge angle, 90°; windshield angle, 32°; air-jet pressure, 35.5 pounds per square inch; total jet-air flow, 6.5 pounds per minute; free-stream velocity, 150 miles per hour.